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CONFINEMENT OF COLOR: OPEN PROBLEMS AND PERSPECTIVES

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- EXPERIMENTAL EVIDENCE
- LATTICE: THE DECONFINING PHASE TRANSITION
- DUALITY
- DECONFINEMENT$_{N_f=2}$: A CROSSOVER?
- MECHANISMS OF CONFINEMENT: RESULTS & PERSPECTIVES

1. EXPERIMENTAL EVIDENCE.

- SEARCH FOR QUARKS (1960 →) $q = \pm\frac{1}{3}$, $q = \pm\frac{2}{3}$

NONE OBSERVED (P.D.G.)

$$\frac{n_q}{n_p} \leq 10^{-27}$$ EXPECTED IN S.C.M. $\frac{n_q}{n_p} \simeq 10^{-12}$

$$\sigma_p \equiv \sigma(p+p \to q+X) \leq 10^{-40}\,\mathrm{cm}^2$$ $\left\{ \begin{array}{l} \text{EXPECTED IN} \\ \text{PT. TH } \sigma_p \simeq 10^{-25}\,\mathrm{cm}^2 \end{array} \right.$

SUPPRESSION FACTOR $\rho \leq 10^{-15}$!

- ONLY "NATURAL" EXPLANATION $\rho = 0$
  OR $\frac{n_q}{n_p} \equiv 0$, $\sigma_p \equiv 0$. ['t Hooft]

  CONFINEMENT: AN ABSOLUTE PROPERTY OF VACUUM BASED ON SYMMETRY (LIKE SUPERCONDUCTIVITY, $m_\gamma = 0$)

$$\Downarrow$$

- DECONFINEMENT: AN ORDER-DISORDER TRANSITION (NOT A CROSSOVER)
  AN ORDER PARAMETER EXISTS, BY WHICH A PRECISE DEFINTION OF CONFINED AND DECONFINED CAN BE GIVEN.

- "UN-NATURAL" ALTERNATIVE. CONFINED-TO-DECONFINED A CROSSOVER'S GO CONTINUOSLY FROM ONE SIDE TO THE OTHER $\rho \neq 0$, BUT VERY SMALL IN CONFINED. NO OPERATIVE DEFINITION $\exists$ OF CONFINED & DECONFINED (NO ORDER PARAMETER)

- NO DATA EXIST ON CONFINEMENT OF GLUONS

- DEFINITION OF CONFINEMENT:
  $\equiv$ ABSENCE OF COLORED PARTICLES IN ASYMPTOTIC STATES

2. LATTICE: THE DECONFINING PHASE TRANSITION.

- CABIBBO-PARISI (1975): THE HAGEDORN LIMITING TEMP. T_H COULD INDICATE DECONFINEMENT.

- INVESTIGATE BY LATTICE SIMULATIONS AT FINITE TEMPERATURE. IN FIELD THEORY

$$Z = Tr\{e^{-\frac{1}{T}H}\} = \int [d\varphi]\, e^{-\int d^3x \int_0^{1/T} d\tau\, \mathcal{L}[\vec{x},\tau]}$$

P.B.C. FOR BOSONS A.B.C. FOR FERMIONS.

- QCD $\quad L_s^3 \times L_t \qquad L_s \gg L_t$

$$T = \frac{1}{a\, L_t} \qquad \begin{cases} a \equiv \text{LATTICE SPACING} \\ a = a(\beta, m) \qquad \beta = \dfrac{2N}{g^2} \end{cases}$$

REN. GROUP $\qquad a \simeq \frac{1}{\Lambda_L} e^{\beta/2b_0}$.

$$b_0 = -\frac{1}{4\pi^2}\left\{\frac{11}{3}N_c - \frac{2}{3}N_f\right\} < 0 \quad \text{(ASYMPTOTIC FREEDOM)}$$

$$T \propto e^{\frac{1}{2|b_0|}\beta} = e^{\left(\frac{2N_c}{2|b_0|}\frac{1}{g^2}\right)}$$

g LARGE (DISORDER) $\Longleftrightarrow$ LOW T

g SMALL (ORDER) $\Longleftrightarrow$ HIGH T

- QUENCHED THEORY (NO QUARKS)

$\vec{r} \equiv \vec{x} - \vec{y}$

$$V(\vec{r}) = -T \ln \mathcal{D}(\vec{r})$$

$$\mathcal{D}(\vec{r}) = \langle L^{+}(\vec{x})\, L(\vec{y})\rangle \underset{|\vec{r}|\to\infty}{\simeq} |\langle L\rangle|^{2} + K\, e^{-\frac{\sigma r}{T}}$$

(CLUSTER PROPERTY)

$|\langle L\rangle| = 0 \qquad V(\vec{r}) \underset{|\vec{r}|\to\infty}{\simeq} \sigma r$ (CONFINEMENT)

$|\langle L\rangle| \neq 0 \qquad V(\vec{r}) \underset{r\to\infty}{\simeq} \text{const}$ (DECONFINEMENT)

$$\boxed{\langle L\rangle \text{ ORDER PARAMETER ; SYMMETRY } Z_3}$$

$\exists \;\; T_c \simeq 270\,\text{MeV} \qquad T > T_c \;\; \langle L\rangle \neq 0$
$\qquad\qquad\qquad\qquad\qquad\qquad T < T_c \;\; \langle L\rangle = 0$

FINITE SIZE SCALING:

TRANSITION IS WEAK FIRST ORDER.

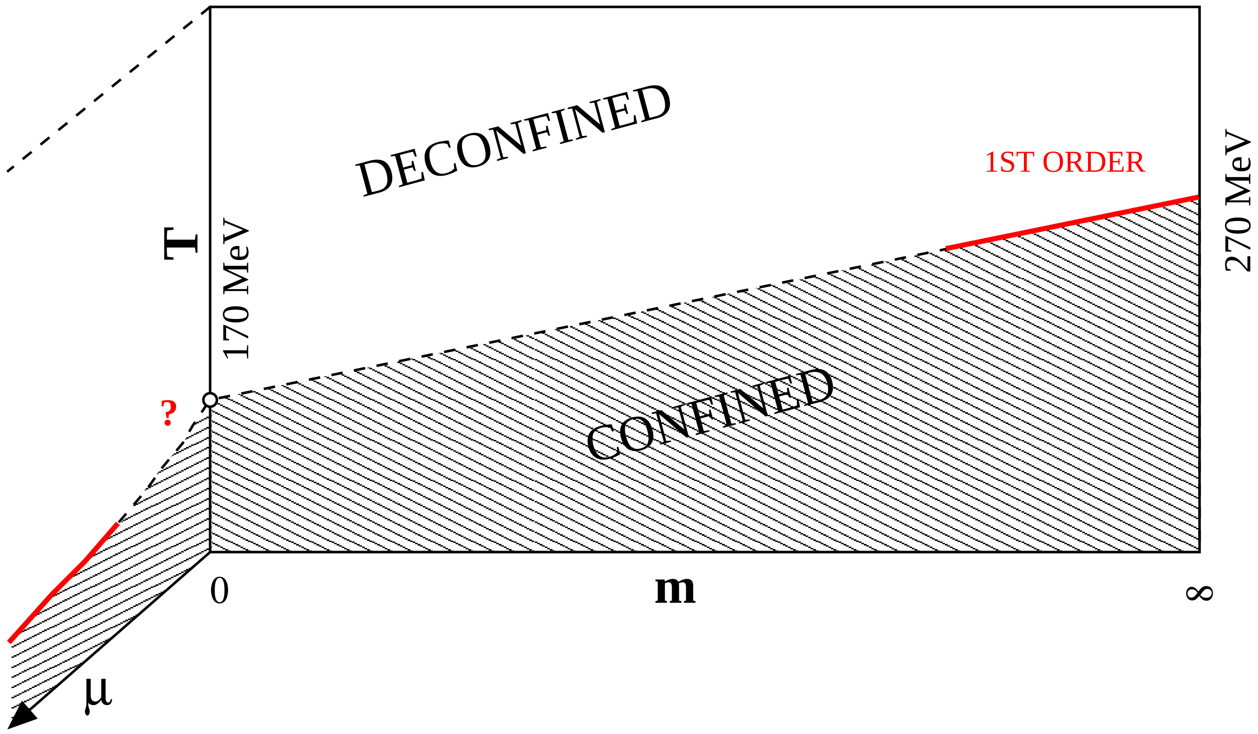
- FULL QCD $(N_f = 2)$
  - STRING BREAKING.
  - Z_3 NOT A SYMMETRY

HOW TO DEFINE CONFINED & DECONF.?

FIG 1 — SAME DIFFICULTY AS IN EXPERIMENT

- $m = 0$ CHIRAL TRANSITION $\langle\bar\psi\psi\rangle$ ORDER PAR.
- $m \to \infty$ QUENCHED $\langle L\rangle$ ORDER PARAMETER
- $m \neq 0$? NEITHER $\langle L\rangle$ NOR $\langle\bar\psi\psi\rangle$ ARE GOOD ORDER PARAMETERS.
- TRANSITION LINE: ABRUPT CHANGE IN $\langle L\rangle$, $\langle\bar\psi\psi\rangle$, $\langle H\rangle$ OR A PEAK IN THE SUSCEPTIBILITIES C_V, $\chi_{\langle L\rangle}$, $\chi_{\bar\psi\psi}$: $\chi_L = \int d^3x \{\langle L(\vec{x})\, L(0)\rangle - \langle L\rangle^2\}$

DECONFINEMENT?



DECONFINED
1ST ORDER
T
170 MeV
270 MeV
?
CONFINED
0
m
∞
μ

- THE CHIRAL TRANSITION [Pisarski; Wilczek 84]

$$\underset{\sim}{\Phi} : \Phi_{ij} = \langle \bar{\psi}_i (1+\gamma_5) \psi_j \rangle \qquad i,j = 1,2 \dots N_f$$

$$\underset{\sim}{\Phi} \to e^{i\alpha} U_L \underset{\sim}{\Phi} U_R \qquad SU(N_f) \otimes SU(N_f) \otimes U_A(1)$$

$$\mathcal{L}_{eff} = \frac{1}{2} Tr[\partial_\mu \phi^+ \partial_\mu \phi] - \frac{m^2}{2} Tr[\phi^+ \phi] - \frac{\pi^2}{3} g_1 [Tr(\phi^+\phi)]^2$$

$$- \frac{\pi^2}{3} g_2 Tr[(\phi^+\phi)^2] + c\,[\det\phi + \det\phi^+]$$

Wess-Zumino term.

$N_f \geq 3$ $[\det\phi] \sim [m]^3$ $O(4) \times O(2)$ NO I.R. STABLE FIXED POINT $\longrightarrow$ 1st ORDER

$N_f = 2$ $[\det\phi] \sim [m^2]$ (i) $c \neq 0$ at T_c $O(4)$ 2nd Or.
(ii) $c = 0$ at T_c $O(4) \times O(2)$ 1st Ord.

(i) CROSS-OVER AT m $(\mu) \neq 0$. A TRICRITICAL POINT AT $\mu \neq 0$ [Shuryak - Stephanov]

(ii) FIRST ORDER AT m $(\mu) \neq 0$, NO TRICRITICAL POINT

(i) "UNNATURAL" $\rightarrow$ NO ORDER PARAMETER

(ii) NATURAL $\longrightarrow$ ORDER - DISORDER

$\Downarrow$

INVESTIGATE ON THE LATTICE.

3. DUALITY

QCD $\begin{cases} \text{HIGH } T & \text{ORDER} \\ \text{LOW } T & \text{DISORDER} \end{cases} \Longrightarrow$

- **DUALITY**: A DEEP CONCEPT IN STATISTICAL MECHANICS, FIELD THEORY, STRING THEORY
[KRAMERS, WANNIER '43, KADANOFF-CEVA 71]

- APPLIES TO SYSTEMS WITH NON LOCAL, TOPOLOGICALLY NON TRIVIAL EXCITATIONS.
- THESE SYSTEMS ADMIT TWO COMPLEMENTARY (EQUIVALENT) DESCRIPTIONS

DIRECT	DUAL
LOCAL FIELDS ϕ	μ ARE LOCAL FIELDS
$\langle\phi\rangle$ ORDER PARAMETERS	$\langle\mu\rangle$ (DIS)ORDER PARAMETERS
μ NON LOCAL TOPOLOGICAL EXCITATIONS	ϕ NON LOCAL EXCITATIONS
CONVENIENT AT $g \ll 1$ (WEAK COUPLING)	CONVENIENT AT $g \gg 1$ (STRONG COUPLING) $g_D \simeq \frac{1}{g}$

DUALITY MAPS THE STRONG COUPLING REGIME OF DIRECT INTO THE WEAK COUPLING OF DUAL.
AND VICE VERSA.

- PROTOTYPE THEORY: 2d ISING MODEL
(1+1)d FIELD THEORY
[KADANOFF-CEVA 71]

$\phi \qquad \sigma = \pm 1 \qquad \langle\sigma\rangle \neq 0 \quad T < T_c$

$\langle\sigma\rangle = 0 \quad T > T_c$

DUAL EXCITATIONS KINKS μ $\downarrow \cdots \downarrow\downarrow\downarrow\downarrow \uparrow\uparrow\uparrow\uparrow\uparrow \ldots \uparrow$

$\mu^2 = 1 \quad \mu = \pm 1$

$\beta = \frac{1}{T} \qquad K[\{\sigma\}, \beta] = K[\{\mu\}, \beta^*]$

$$\sinh(2\beta) = \frac{1}{\sinh(2\beta^*)} \qquad \beta^* \sim \frac{1}{\beta}$$

$\langle\mu\rangle \neq T > T_c \quad \langle\mu\rangle = 0 \; T < T_c$.

- QCD LOW T (STRONG COUPLING, DISORDERED)
  ORDERED IN THE DUAL LANGUAGE
  $\langle\mu\rangle$ THE ORDER PARAMETERS ['tHooft 78]

$\Downarrow$

IDENTIFY THE DUAL SYMMETRY AND THE CORRESPONDING TOPOLOGICAL EXCITATIONS.

- SOLITONS IN 3+1 d, MADE STABLE BY TOPOLOGY $G \to H \quad \pi_2(G/H) \neq \{1\}$

  $G = SU(3) \qquad H = SU(2) \otimes U(1) \to$ MONOPOLES
  ['tHooft 74, POLYAKOV 74]

  $\pi_2(G/H) = Z^2$ [TWO MONOPOLE SPECIES]

  $\pi_2(SU(3)/Z_3) = \{1\}$

- IN 2+1 d $\cancel{\pi_1(SU(3)/Z_3) =}$ $G \to H \quad \pi_1(G/H)$

  $\pi_1(SU(3)/Z_3) = Z^2 \longrightarrow$ VORTICES

  [IN ABSENCE OF DYNAMICAL QUARKS]

4. DECONFINEMENT: THE CASE OF $N_f=2$. A CROSSOVER?

- A FUNDAMENTAL ISSUE: DESERVES MORE ATTENTION AND NUMERICAL EFFORT TO BE SETTLED.

- M. D'ELIA, A. DIGIACOMO C. PICA hep-lat 0503030

1.5 Teraflop × year – LATTICES $4\times16^3, 4\times20^3, 4\times24^3, 4\cdot32^3$

- CAREFUL SCANNING OF CRITICAL PEAKS OF C_V, $\chi_{\langle\bar\psi\psi\rangle}$.

- FINITE SIZE SCALING ANALYSIS (RENORMALIZATION GROUP), (L_s THE SPACIAL SIZE OF THE LATTICE)

$$C_V - C_0 = L_s^{\alpha/\nu}\,\phi_c\left(\tau L_s^{1/\nu}, m L_s^{y_h}\right)$$
$$\chi - \chi_0 = L_s^{\gamma/\nu}\,\phi_\chi\left(\tau L_s^{1/\nu}, m L_s^{y_h}\right)$$

$$\tau = 1-\frac{T}{T_c} = 1-\frac{a(\beta_c,0)}{a(\beta,m)}$$

A TWO SCALE PROBLEM

U.C. \ INDEX	$1/\nu$	y_h	α	γ	δ
O(4)	1.336(25)	2.487(3)	-.24(6)	.3837(69)	4.852(24)
O(2)	1.496(20)	2.485(3)	-.005(7)	.3442(20)	4.826(12)
W. 1st ORD	3	3	1	1	∞

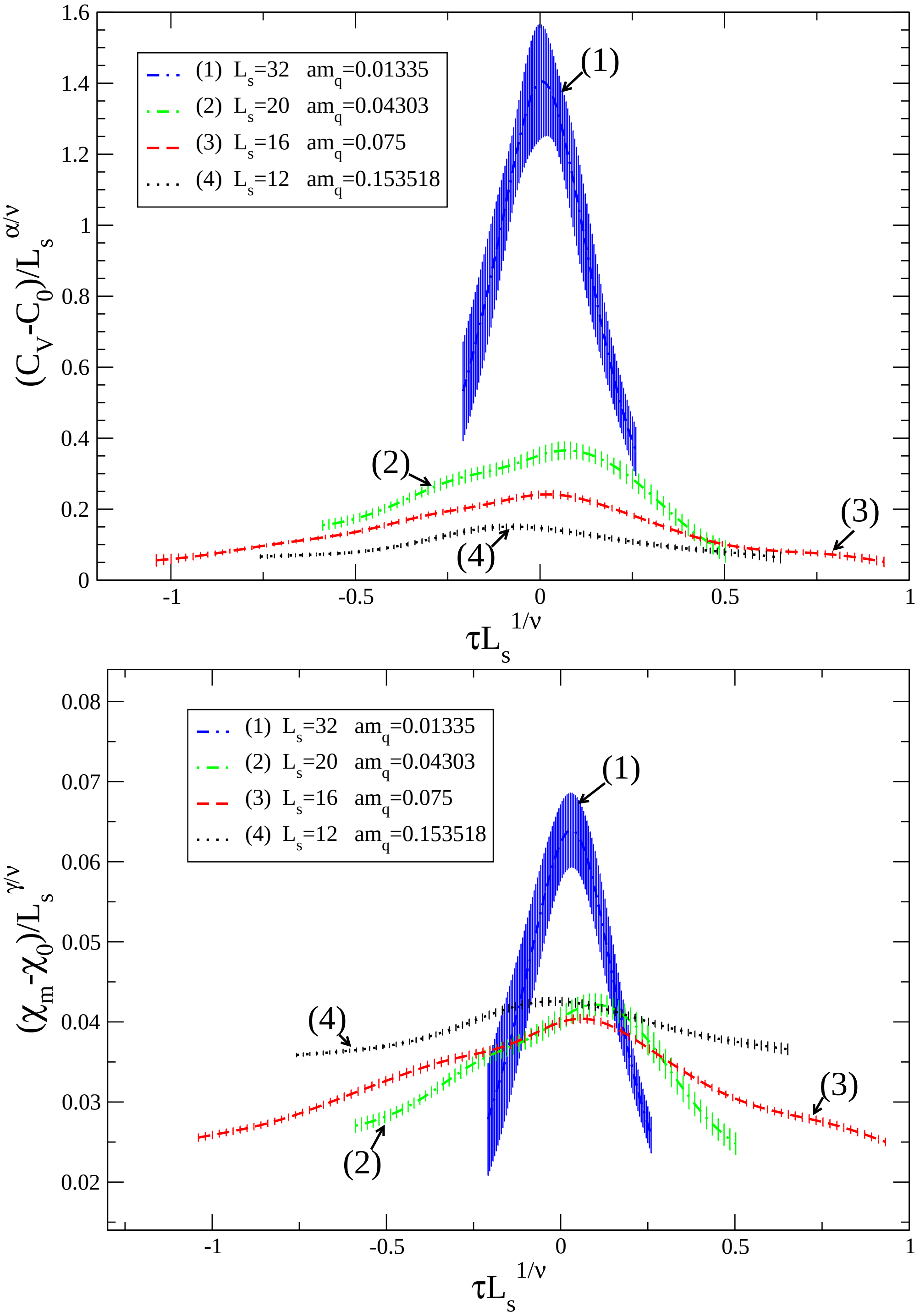
- C_V IS INDEPENDENT ON PREJUDICE ABOUT THE ORDER PARAMETER.

- STRATEGY #1: y_h THE SAME FOR O(2), O(4): KEEP $m L_s^{y_h}$ FIXED WHEN CHANGING m, L_s.

- $(C_V - C_0)/L_s^{\alpha/\nu} = \bar\Phi\left(\tau L_s^{1/\nu}\right)$: TO BE CHECKED

2 RUNS $m L_s^{y_h} = C_t$; FIG. 5

Run1


(1) L_s=32 am_q=0.01335
(2) L_s=20 am_q=0.04303
(3) L_s=16 am_q=0.075
(4) L_s=12 am_q=0.153518
$(C_V-C_0)/L_s^{\alpha/\nu}$
$\tau L_s^{1/\nu}$
$(\chi_m-\chi_0)/L_s^{\gamma/\nu}$
$\tau L_s^{1/\nu}$

- STRATEGY #2 $L_s >> \frac{1}{m_\pi}$

$$C_V - C_0 \simeq m^{\alpha/\nu y_h} f_c(\tau L_s^{1/\nu})$$
$$\chi - \chi_0 \simeq m^{\gamma/\nu y_h} f_\chi(\tau L_s^{1/\nu})$$

CHECK FOR O(4) O(2)
1st ORDER

FIG.

CONSISTENT WITH 1st ORD

- STRATEGY #3 LOOK AT THE MAGNETIC EQ OF STATE

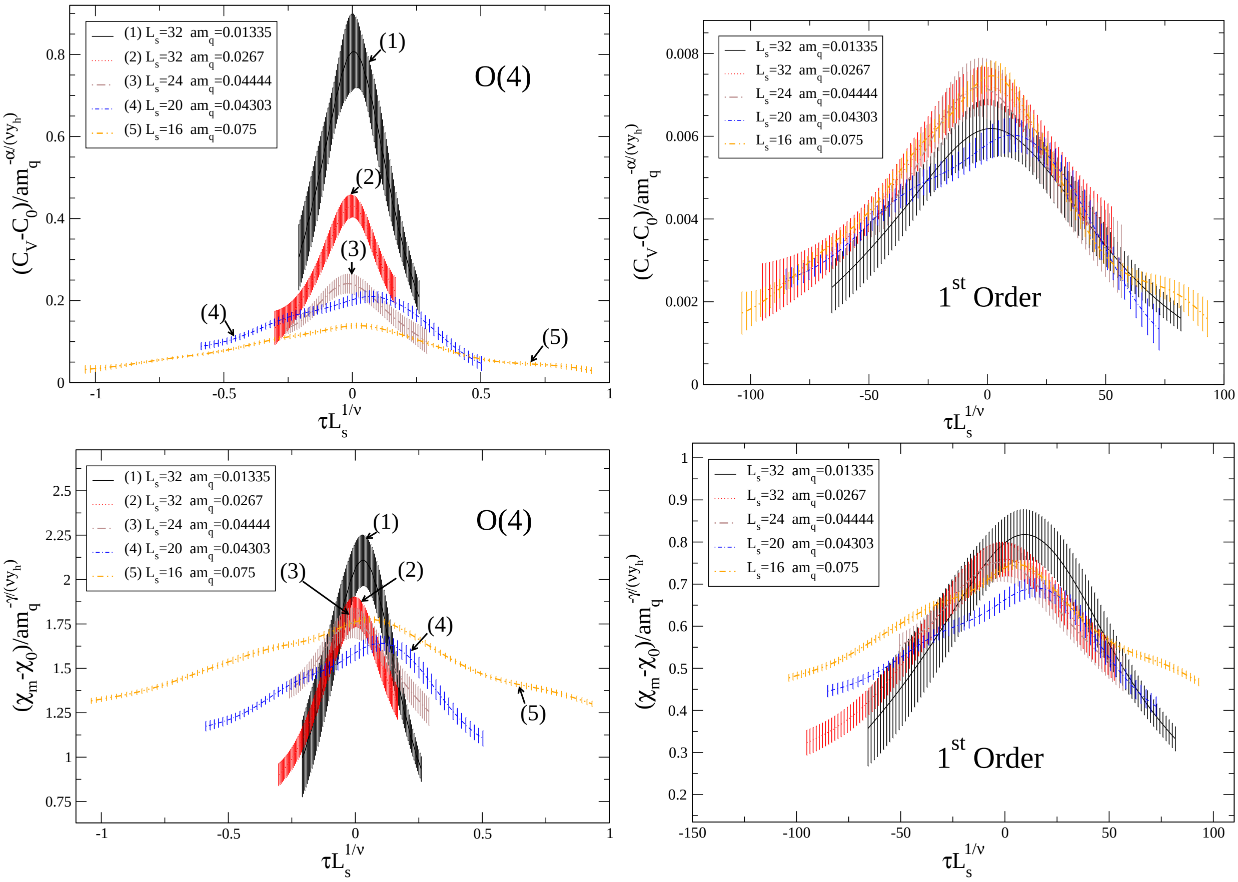
$$\langle\bar\psi\psi\rangle - \langle\bar\psi\psi\rangle_0 = m^{1/\delta} f(\tau m^{-1/\nu y_h})$$

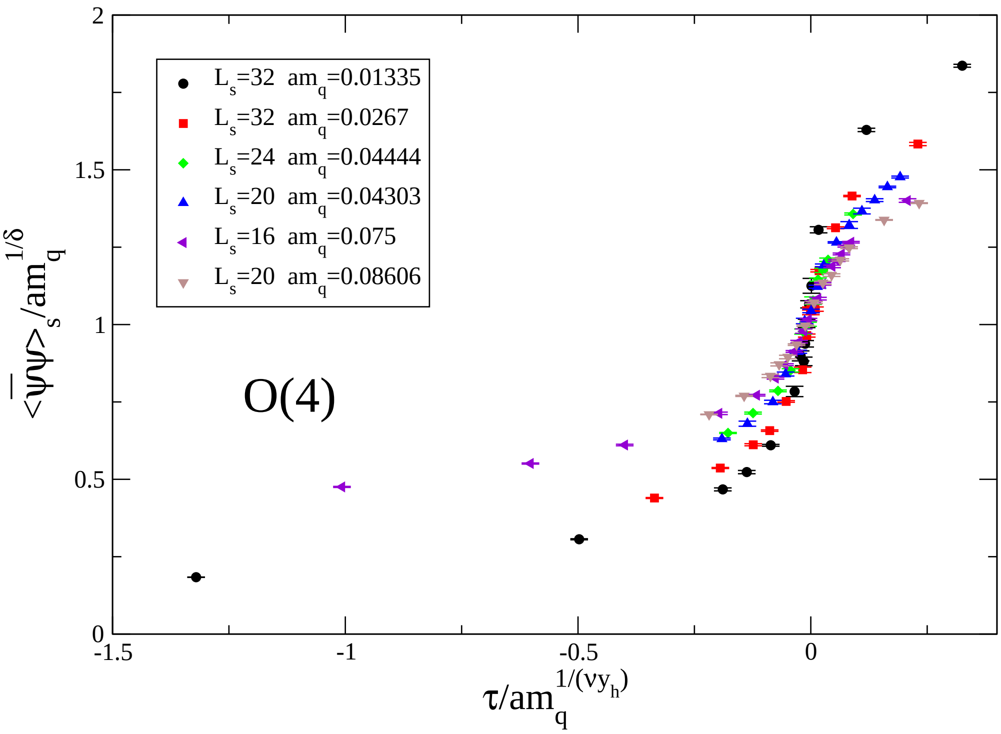
CONSISTENT WITH
1st ORDER

- LOOK FOR METASTABILITIES : NO CONVINCING EVIDENCE

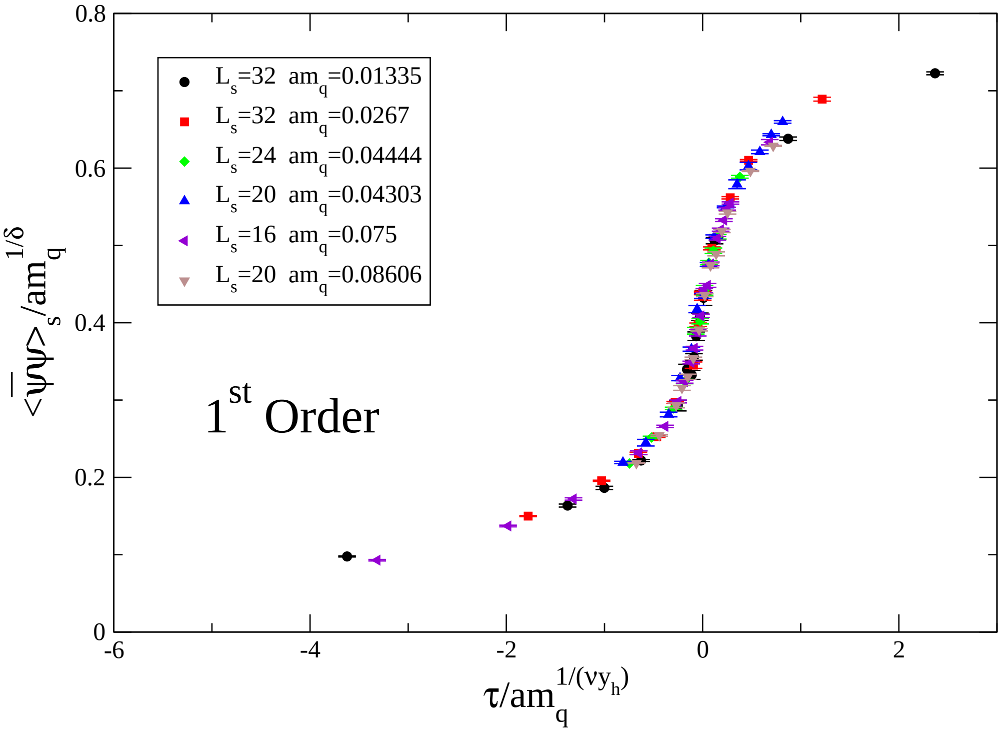
- CONCLUSION
  - O(4) [O(2)] 2nd ORDER EXCLUDED $(\chi^2_{/dof} \simeq 50)$
  - SCALING CONSISTENT WITH 1st ORDER
  - VOLUMES NOT BIG ENOUGH TO DETECT METASTABILITY ?

- RESEARCH GOING ON WITH IMPROVED ALGORITHM, IMPROVED ACTION, LARGER LATTICES


(1) Ls=32 amq=0.01335
(2) Ls=32 amq=0.0267
(3) Ls=24 amq=0.04444
(4) Ls=20 amq=0.04303
(5) Ls=16 amq=0.075
O(4)
1st Order
(CV-C0)/amq^-α/(νyh)
(χm-χ0)/amq^-γ/(νyh)
τLs^1/ν



O(4)
L_s=32 am_q=0.01335
L_s=32 am_q=0.0267
L_s=24 am_q=0.04444
L_s=20 am_q=0.04303
L_s=16 am_q=0.075
L_s=20 am_q=0.08606
$\langle\bar{\psi}\psi\rangle_s/am_q^{1/\delta}$
$\tau/am_q^{1/(\nu y_h)}$



1st Order
L_s=32 am_q=0.01335
L_s=32 am_q=0.0267
L_s=24 am_q=0.04444
L_s=20 am_q=0.04303
L_s=16 am_q=0.075
L_s=20 am_q=0.08606
$\langle\bar{\psi}\psi\rangle_s/am_q^{1/\delta}$
$\tau/am_q^{1/(\nu y_h)}$

5 MECHANISMS OF CONFINEMENT: RESULTS AND PERSPECTIVES.

- RECENT PROGRESS IN CURRENT APPROACHES

1) SEARCH FOR SYMMETRY [BARI, PISA, ITEP (marginally)]

MONOPOLES : μ A MAGNETICALLY CHARGED OPERATOR $\langle \mu \rangle \neq 0 \Rightarrow$ DUAL SUPERCONDUCTIVITY

STATUS • $\langle \mu \rangle \neq 0 \quad T < T_c$

$\langle \mu \rangle \equiv 0 \quad T > T_c$

QUENCHED, UNQUENCHED $N_f = 2$ ABELIAN PROJECTION INDEPENDENT

• $T \simeq T_c \qquad \rho \equiv \frac{\partial \ln \langle \mu \rangle}{\partial \beta}$

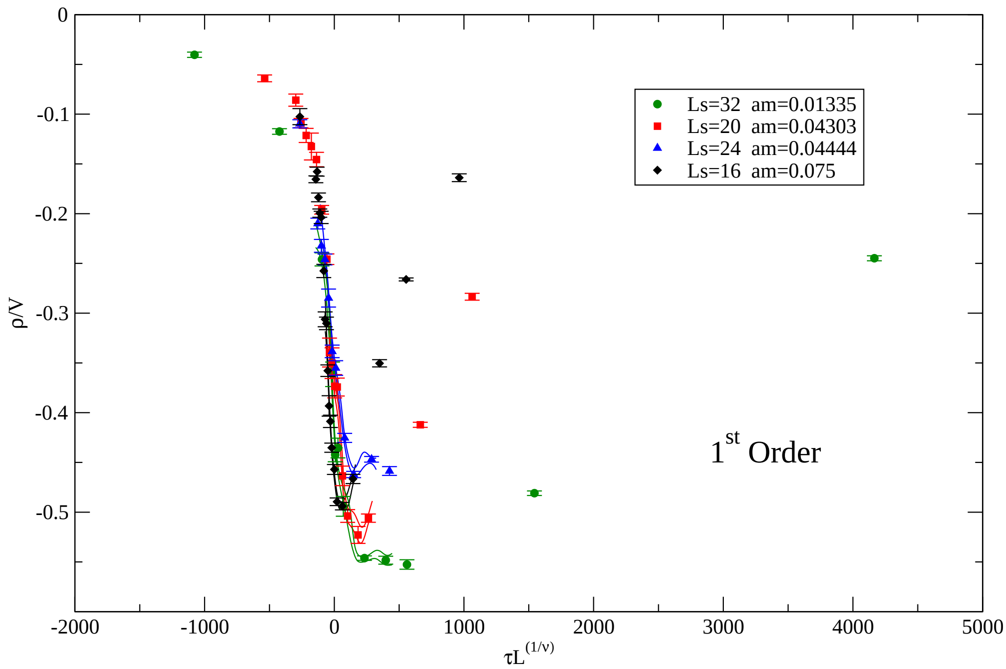
FINITE SIZE SCALING $\qquad \rho / L_s^{1/\nu} = \phi(\tau L_s^{1/\nu})$

$N_f = 2$ [D'Elia, A. DG, C.P. Phys Rev D71, 114502 2005] fig.

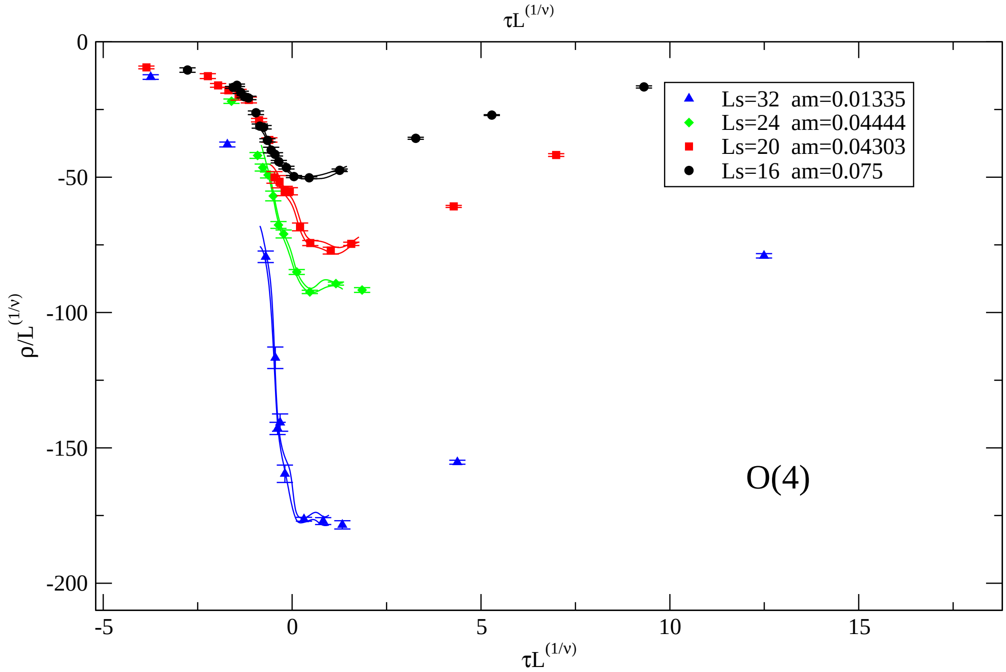
[SEE ALSO CEA et AL JHEP 04002:018 2004]
CONSISTENT WITH 1st ORDER

THESE DATA, TOGETHER WITH PREVIOUS DATA ON QUENCHED THEORY, IMPLY THAT

- CONFINING VACUUM IS A DUAL SUPERCONDUCTOR AT $T < T_c$, NORMAL AT $T > T_c$. (THE DEC. TRANSITION IS ORDER-DISORDER)
- WHATEVER THE DUAL EXCITATIONS THEY ARE MAGNETICALLY CHARGED IN ALL ABELIAN PROJECTIONS.



Ls=32 am=0.01335
Ls=20 am=0.04303
Ls=24 am=0.04444
Ls=16 am=0.075
1st Order
ρ/V
τL(1/ν)



Ls=32 am=0.01335
Ls=24 am=0.04444
Ls=20 am=0.04303
Ls=16 am=0.075
O(4)
ρ/L(1/ν)
τL(1/ν)

2 APPROACH CHOOSING A SPECIAL GAUGE

[MAX. ABELIAN, MAX CENTER GAUGE]

TO EXPOSE THE NON LOCAL EXCITATIONS (MONOPOLES, VORTICES) (ITEP, KANAZAWA] (SAN FRANCISCO, TUBINGEN, ZÜRICH, ...)

• "SURGICAL" ANALYSIS : ELIMINATE SOMEHOW THE EXCITATIONS AND CHECK THAT PHYSICAL PROPERTIES DISAPPEAR. ⇒ CLAIMS THAT CONFINEMENT MECHANISM IS UNDERSTOOD

3 ANALYZE SEVERAL GAUGE GROUPS

WITH THE SAME CENTER TO EXPLORE THE ROLE OF VORTICES [BERN HOLLAND ET AL NUCL. PHYS. B 668, 207, 2003

INTERESTING RESULT : G_2 GAUGE GROUP CONFINES AND HAS NO CENTER.

4 PHENOMENOLOGY OF MONOPOLES IN MAX. ABELIAN GAUGE. GUESS THEIR DYNAMICS [ZAKHAROV + ITEP] DIMENSIONALITY OF EXCITATIONS.

UNDERSTANDING OF CONFINEMENT : STILL AN OPEN PROBLEM.

PERSPECTIVES

- CLARIFY THE ISSUE OF ORDER-DISORDER V.S. CROSSOVER.

- CLARIFY MANY ASPECTS OF CONFINEMENT IN G_2, A NON INVASIVE METHOD TO UNDERSTAND THE ROLE OF VORTICES

- TRY TO GET CONNECTION WITH ANALYTIC RESULTS [Seiberg Witten N=2 SUSY]
  IN THAT RESPECT THE IDEAS ABOUT $N_c \to \infty$ [ARMONI, SHIFMAN VENEZIANO
  e.g. FORTSCH. PHYSIK 52, 453, 2004.